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Economics of Fertilizer Use in Brazil

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Abstract

The response to fertilizers in one region of São Paulo is analyzed by means of Cobb-Douglas functions and other fertilizer research in Brazil is reviewed. Possible reasons for the apparent lack of response to fertilization are discussed and recommendations are made concerning government policy and research thrusts.

Introduction

The transition to a modern agriculture is marked by the use of a number of new inputs, technological change, and improvement in the quality of traditional inputs. One of the most prominent features of this transition is the rapid increase in use of chemical fertilizers. Over the 1965/66 to 1970/71 period, world-wide fertilizer use increased 48 percent. Usage of chemical fertilizer in South America increased more rapidly, resulting in a 133 percent rise in the same period (7, p. 46). In some cases fertilizer use has been stimulated by dramatic changes in technologies, e.g. new seed varieties which are highly responsive to plant nutrients, irrigation, or mechanization. In other cases, fertilizer use has been spurred by concessional prices, credit incentives, or educational programs. By almost any measure, chemical fertilizer has become and will likely continue to be considered a key factor in accelerating agricultural development.

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This paper focuses on recent changes in fertilizer utilization in Brazil. The objectives of the paper are: (1) to review studies estimating crop response to fertilization in Brazil; and (2) to suggest policy changes and research priorities based on the results of the first objective.

In many respects, Brazil is an excellent case to study with regard to the economics of fertilizer application. It has experienced rapid changes in fertilizer usage in the past 20 years and has also employed a variety of policy instruments to encourage these changes. On the output side, minimum support prices were established for most food crops. At various times, fertilizer received concessional import exchange rates and special subsidized credit. The Agency for International Development (AID) supported these efforts during the 1960's with loans and loan guarantees totaling $67.9 million dollars for new production facilities and programs designed to stimulate utilization (1, pp. 28-38). As a result, fertilizer consumption in Brazil has increased 272 percent, from 257,052 tons (metric) in 1965/66 to 957,216 tons in 1970/71, and the private fertilizer marketing system has expanded accordingly (7, p. 46). The rate of fertilizer application has also increased from 8.64 Kg. per arable hectare in 1965/66 to 32.2 Kg. in 1970/71. Brazilian consumption remains low, however, relative to United States usage of 86.8 Kg. per arable hectare and average world consumption of 47.4 Kg. per arable hectare in 1970/71.

Productivity is also low relative to United States and world averages (Table 1). Brazilian yields of corn, cotton, and rice were only one-third of United States yields in these crops. Only in the production of soybeans has Brazil approached world average yields (8).

Although fertilization rates have increased rapidly, there is a lack of information available on crop response to fertilizer at the farm level in

TABLE 1. AVERAGE YIELDS OF VARIOUS CROPS IN BRAZIL, UNITED STATES, AND WORLD, 1969/70.

Crops	Brazil	United States	World
		(Kilograms/hectare)	
Corn	1,470	4,500	2,410
Cotton	690	1,350	1,010
Rice	1,640	5,120	2,260
Soybeans	1,250	1,800	1,330

SOURCE: Food and Agriculture Organization of the United Nations, Production Yearbook-1970, Volume 24, (Rome, 1971), pp. 37, 57, 73, and 228.

Brazil. The type of government programs to increase agricultural production in the future will depend to a large extent on actual crop response to fertilization. For example, if fertilizer application is yielding high net returns and the adoption process is nearly complete, the need for economic concessions and promotional activities has passed. If fertilizer application is not yielding high net returns to the farmer, a strategy of crop and soil research is needed to shift the response to fertilizers.

Response to Fertilization

Analysis of the marginal product of fertilizer is central to the study of the economics of fertilizer utilization. The return to fertilization has been estimated to be US $2.50 for each dollar spent for fertilizer in the United States.[1] Another study on fertilizer consumption assumed that increases of 20 to 40 percent in fertilizer use in Latin America would yield a 25 percent increase in production.[2]

The response to fertilization in Brazil has been documented in both formal experiments and informal observations, although most of these reports have not been designed to facilitate the process of making economic recommendations. This problem is emphasized in the following statement. (15)

> "Recently, we worked on a research project to analyze the increase in production and use of fertilizer in Brazil,---. It was not difficult to gather 400 studies and experiments with fertilizer elements isolated or combined, but it was practically impossible to determine some idea of application levels given price information. This demonstrates the lack of suitability of the studies for economic interpretation.'

This conclusion is shared by Rice, (17, p. 175) who states:

> "It is appalling how little research there has been on the profitability of inputs and how few reliable reports on the subject can be found in most of Latin America.'

Ribeirão Preto Study

As part of a project on factors affecting the rate of capital formation in Brazilian agriculture, an analysis of crop response to fertilization was made during 1970/71. The data were based on personal interviews with 174 farmers from the Ribeirão Preto region, state of Sao Paulo, Brazil.[3] This region was selected because of its variety of annual crops, extensive use of fertilizer, progressive nature of the farmers, and a highly developed rural infrastructure. Each of the 174 farms was randomly selected from a population of farms containing over 50 percent of their cultivated land in annual crop production.

Actual fertilizer use was greater than expected. Previous Brazilian studies indicated average use levels from 10 to 50 kilograms per hectare; however, an average of nearly 83 kilograms per hectare was used in this region. Only two of the sample farmers did not use fertilizer during the 1969/70 agricultural year. Utilization was not high relative to minimum recommendations (3) (Table 2). The use of nitrogen was particularly low ranging from 24 percent for corn to 94 percent for soybeans of the recommended level. At the other end of the spectrum, potassium was applied at an average rate of 132 percent of the recommendations.

TABLE 2. — COMPARISON OF FERTILIZER RECOMMENDATIONS TO ACTUAL FARM USE IN THE RIBEIRAO PRETO REGION, 1969/70[a]

Fertilizer and Crop	Recommendation[b] (kg/ha.)	Actual Use (kg/ha.)	Actual Use as % of Minimum Recommendation
Cotton			
(1) Nitrogen	32 - 79	18.16	56%
(2) Phosphate	60 - 119	75.79	127%
(3) Potash	48 - 119	47.28	100%
(4) Total	140 - 317	141.12	102%
Rice			
(1) Nitrogen	12 - 32	6.95	56%
(2) Phosphate	18 - 95	30.76	52%
(3) Potash	12 - 62	13.13	106%
(4) Total	42 - 189	50.84	60%
Corn			
(1) Nitrogen	59 - 68	14.08	24%
(2) Phosphate	45 - 89	33.23	74%
(3) Potash	9 - 18	21.26	234%
(4) Total	113 - 175	68.57	61%
Soybeans			
(1) Nitrogen	9 - 18	8.53	94%
(2) Phosphate	45 - 60	46.12	103%
(3) Potash	9 - 18	33.04	364%
(4) Total	63 - 96	87.69	140%
All Crops			
(1) Nitrogen	35	12.45	36%
(2) Phosphate	52	46.20	89%
(3) Potassium	18	24.12	132%
(4) Total	105	82.77	79%

[a]Fertilizer expressed in nutrients.
[b]Associacão Nacional para Difusão de Adubos, "Sugestoẽs Gerais De Adubacõ," unpublished paper, São Paulo, 1970, p. 13.

SOURCE: Associacão Nacional para Difusão de Adubos, "Sugestoes Gerais De Adubacõ," unpublished paper, (Sao Paulo, 1970), p. 13, and William C. Nelson, "An Economic Analysis of Fertilizer Utilization in Brazil," unpublished Ph.D. dissertation, (Columbus: The Ohio State University, 1971), p. 59.

Yields of corn and cotton in the Ribeirao Preto region were 2,641 and 1,230 kilograms per hectare, respectively, nearly twice the national average. Rice and soybean yields were 1,705 and 1,593 kilograms per hectare, respectively, only slightly over the national average.

Production Function Analysis

The analysis of crop response to fertilization was performed on a per hectare basis. Two Cobb-Douglas functions, presented in Table 3, consistently yielded better results in terms of statistical significance and economic logic than other models.[4] These two equations were estimated by using an aggregate yield index and a summation of inputs in all crops and dividing by the summation of crop area for each farm.[5]

Lime, fertilizer, seed and chemicals, labor and machinery and the management index produced positive coefficients in relation to yield while cultivated land was negative (Model I). The fertilizer variable was statistically insignificant, however, and the regression coefficient was approximately zero, indicating nearly no response to fertilizer. All variables except seed and chemicals had values of marginal product less than the input prices, which suggests that the use of these factors should be reduced. When the fertilizer variable was separated into its nutrients, nitrogen yielded a significant negative production response, while phosphate and potash were positive (Model II).

Profitability

Analysis of profitability yielded conclusions which were still more disconcerting. Although positive values of the marginal product (VMP) of fertilizer were obtained, the marginal net income could still be negative when the cost of fertilizer is subtracted. As seen in Table 4, the marginal net income was generally negative. In the regional analysis, there was no case where the marginal net income of fertilizer (NPK) was positive, i.e., where the value of marginal product exceeded the cost of fertilizer.[6] Marginal net income was positive only for potash and nitrogen in soybean production.

TABLE 3. REGIONAL ALL-CROP PRODUCTION FUNCTIONS

	Model I Regression Coefficients[a]	Model I VMP[b] (Cr$)	Model II Regression Coefficients[a]	Model II VMP[b] (Cr$)
Constant	2.130		2.255	
X_1 - Lime	0.014[c] (0.016)	4.36	0.018[c] (0.016)	5.60
X_2 - Nitrogen			-0.067[d] (0.025)	-5.36
X_3 - Phosphate			0.014 (0.022)	0.33
X_4 - Potash			0.036[c] (0.023)	1.90
X_5 - All Fertilizer	0.003 (0.021)	0.03		
X_7 - Seed and Defensives	0.203[d] (0.029)	4.66	0.198[d] (0.029)	4.55
X_9 - Labor and Machinery	0.098[d] (0.036)	0.32	0.109[d] (0.036)	0.35
X_{11} - Management Index	0.145[d] (0.084)	0.11	0.126[c] (0.082)	0.10
X_{13} - Cropland	-0.031[c] (0.028)	-1.88	-0.039[c] (0.028)	-2.36
Standard Error of Estimate	0.394		0.353	
Simple R^2	0.360		0.426	
F-Ratio	15.621[d]		13.181[d]	

[a]Numbers in parentheses are the standard errors.

[b]VMP's are calculated at the geometric means of the variables.

[c]Significant at 0.25 level (one tailed test except X_{13}).

[d]Significant at 0.05 level (one tailed test except X_{13}).

SOURCE: Nelson, William C., "An Economic Analysis of Fertilizer Utilization in Brazil,' unpublished Ph.D. dissertation, (Columbus: The Ohio State University, 1971), p. 85.

TABLE 4. VALUE OF THE MARGINAL PRODUCT OF FERTILIZER BY NUTRIENTS, LEVEL OF USE AND CROP

Sample	Value of Marginal Product in Cruzeiros/Kg.[a]			
	Nitrogen	Phosphate	Potash	All Fertilizer
Ribeirao Preto Region				
Corn	-2.80	0.46	1.22[b]	0.11
Rice	-12.42	-3.84	4.85	-1.94
Cotton	-3.88	0.93[b]	0.71	0.14
Soybeans	1.88	-0.70	2.94	0.19
All Crops	-5.36[c]	0.33[b]	1.90[b]	0.03
High Group				
Corn	-2.04	0.18	3.16[b]	1.15[c]
Rice	-9.12	-1.55	3.38	1.40[b]
Cotton	-0.75	2.37[c]	1.13	1.63[b]
Soybeans	-15.17	0.93	0.52	0.02
Low Group				
Corn	-4.46	1.38	0.71	-0.09
Rice	-22.13	-11.84	18.79[b]	-3.76
Cotton	-6.07	-0.62	-3.35	0.44
Soybeans	-72.42	-13.05	23.38	-2.34

[a] Value of marginal product is calculated at geometric means based on coefficients from Cobb-Douglas type equations. Prices are: (1) Cotton, Cr$10.70/15 kg.; (2) Rice, Cr$21.15/60 kg.; (3) Corn, Cr$10.00/60 kg.; (4) Soybeans, Cr$27.80/60 kg.; (5) Nitrogen, Cr$1.08/kg.; (6) Phosphate, Cr$0.96/kg.; (7) Potash, Cr$0.43/kg.; and (8) All Fertilizer, Cr$0.83/kg.

[b] Derived from regression coefficients significant at 0.25 level.

[c] Derived from regression coefficients significant at 0.05 level.

SOURCE: Nelson, William C., "An Economic Analysis of Fertilizer Utilization in Brazil," unpublished Ph.D. dissertation, (Columbus: The Ohio State University, 1971), p. 98.

The situation changed when high and low groups were compared.[7] There were positive values of the marginal products for all fertilizer except in soybean production for the high group.[8] The marginal net income varied from Cr$0.32/kg. of fertilizer for corn to Cr$.80/kg. for cotton with a fertilizer price of Cr$0.83/kilograms. The low group normally had higher net losses than the regional sample except for potash application. The implication of these results is that if fertilizer is applied within the range observed on these farms, the marginal net income is higher or the marginal loss is lower with high application rates.

Other Fertilizer Research

Does the study have any validity for other areas in Brazil or is it a unique case? Fertilizer is claimed to yield production increases of two to ten times the national average yield in experiments on all major crops (13, p. 6). In reviewing previous findings, however, it was difficult to find research reporting consistently high crop response to fertilizers in Brazil.

An informal study of Operation Armadillo in Rio Grande do Sul reported that large increases in the usage of lime (5 to 6 tons per acre) and phosphate (400 to 500 pounds per acre) tripled the yield of soybeans and wheat (20). Low levels of lime and fertilizer previously used in the area had yielded almost no response, thus the author concluded that "until the early 1960's the economists and some soil specialists were so busy emphasizing efficient use of lime and fertilizer that they never realized the importance of sufficient use" (20, p. 9).

The predecessor of Operation Armadillo was not as successful (5). This project in the municipio of Ibiruba, Rio Grande do Sul, had placed emphasis only on soil testing, fertilizer and lime application and credit. Analysis of productivity changes between borrowers (fertilizer users) and nonborrowers (nonfertilizer users) revealed no significant differences in yields. The reasons given for these results were improper timing of fertilizer application, rainfall and insect problems.

Quadratic equations were used by Knight to estimate the response of yield to fertilizer in Rio Grande do Sul and significant coefficients were found for rice, wheat and corn with respect to nitrogen, phosphate and lime (11, pp. 143-163). The responses were at low levels leading to optimum application levels of zero under several of the hypothesized price conditions. Even under conditions of perfect knowledge and favorable prices, optimum nitrogen application was approximately 30 kg/ha. on irrigated rice, 10 to 40 kg/ha. on wheat and 30 to 75 on cotton for the years 1960, 1965 and 1966. Optimum phosphate levels were 60 kg/ha. for irrigated rice, 100 to 140 kg/ha. for wheat and 0 kg/ha. for corn during the same period. No significant response to potash was found. Nonexperimental farm data provided the base for another Rio Grande study in which the total value of fertilizer and other inputs were regressed against the total value of crop production (19, pp. 42-53). Insignificant response to fertilizer was found in this study.

An analysis of fertilizer use in the Northeast was based on a mixture of experimental results and general knowledge of soil scientists in the area (9, pp. 14-27). Budgeting techniques were used to analyze the response of several crops to fertilization. Sugar cane was the only crop in the area for which fertilization increased net returns per hectare. Yields would have to increase 105 percent for edible beans, 400 percent for corn and 120 percent for cotton over present levels in order to profitably apply fertilizer valued at Cr$35.00 per hectare. The author concluded that fertilizer would be a poor investment for most farmers in the Northeast.

A study of the response of cotton yields to fertilizers under experimental conditions in São Paulo found high responses to all nutrients when the initial levels of these nutrients were very low. When the natural levels of the nutrients in the soil were relatively high, however, the application of nitrogen, phosphate or potash decreased production (10, p. 15). Significant response of corn yield to nitrogen and phosphate was found in Minas Gerais (18, pp. 203-208). A later analyses of fertilizer experiments with corn in São Paulo included 50 observations during four years (22). Only nitrogen application was found to be economically profitable, and there was a large variation in the optimum levels of application.

Most of the research on fertilizer use in Brazil has yielded mixed results. A comprehensive 1964 review of fertilizer experiments in Brazil revealed positive responses to phosphate and potash (2, pp. 124-161). Nitrogen did not yield significant increases in crop yields in all experiments. Similarly, estimates of changes in net return due to fertilizer application were positive for phosphate and potash in all cases, but only about half the nitrogen experiments yielded positive net returns.

In summary, the results of fertilization research are mixed and inconclusive (Table 5). Contrary to the popular assumption that fertilizer is a key to unlocking large increases in production in Brazil, this review suggests that increases in fertilization rates under current knowledge may not have a significant positive impact on crop yields. This problem appears to be especially serious for the use of nitrogen.

TABLE 5. SUMMARY OF FINDINGS OF ANALYSES OF RESPONSE TO FERTILIZER

			Crop Response to:[a]			
Researcher	Location	Crop	Nitrogen	Phosphate	Potash	Total
Nelson (14)	São Paulo	Corn	0	0	⊕	⊕
		Cotton	0	⊕	0	⊕
		Rice	0	0	⊕	⊕
		Soybeans	0	0	0	0
		All Crops	-	+	+	0
Agri-Research (2)	São Paulo	Corn	+	+	+	
		Cotton	±	+	+	
		Rice		+		
		Soybeans	+	+		
Steitieh (19)	Rio Grande do Sul	All Crops				0
Frederick (9)	N. E. Brazil	Sugar Cane				+
		Other Crops				0
Fozatto (10)	São Paulo	Cotton	±	±	±	
Knight (11)	Rio Grande do Sul	Rice	+	+	0	
		Wheat	±	±	0	
		Corn	+	0	0	
Santos (18)	Minas Gerais	Corn	+	+	0	
Streeter (20)	Rio Grande do Sul	Soybeans		+		
		Wheat		+		
Vieira (22)	São Paulo	Corn	+	0	0	
Valdeci (21)	São Paulo	Corn				⊕
Lanzer (12)	Rio Grande do Sul	Wheat	+	+	+	

[a]Positive response to fertilizer is signified by +, insignificant or no response by 0, negative by -, and mixed responses by ±, ⊖ or ⊕.

SOURCE: Sources are indicated by the numbers in parentheses by each author.

Factors Affecting the Lack of Response to Fertilizers

These conclusions raise two questions: (1) What factors inhibit a profitable response to fertilizer; and (2) why are farmers presently using nonprofitable quantities and/or combinations of fertilizers?

Response Limitations

The study reported on here did not collect data which could entirely respond to these questions. Several suggestions offered by soil scientists, however, may help one to understand the problem. One limitation could be the soil. The most common soil in the area, terra roxa (red soil), is normally acidic with high levels of iron and bauxite. Nitrogen applied in the form of ammonium sulfate can produce sulfuric acid which will increase the soil acidity. Phosphate fixation can also occur in this soil type, making the nutrient unavailable to plants. The porous quality of the soil can permit "leeching" of fertilizer if heavy rains occur soon after application.

A second alternative is that the present combination of nutrients is inadequate to correct soil deficiencies and/or perhaps there are deficiencies in micronutrients which prevent response to the application of macronutrients.

A third possibility is the application of fertilizer in the wrong time period or applied in an incorrect location relative to the seed.

Another explanation could be that the Brazilian plant varieties do not efficiently respond to chemical fertilizer. Given the local conditions, present varieties may produce relatively less yield per unit of fertilizer than new varieties associated with the "Green Revolution." This would suggest that for any given set of prices, the optimum use of fertilizer and yield will be much lower than in other regions of the world.

A final explanation is suggested by the difference observed between the high and low groups. The rate of fertilizer application by the low group may not be sufficiently high to generate a significant yield response. Perhaps a certain minimum critical rate is necessary to compensate for the limitations mentioned previously and application above this rate may produce an increasing response per unit over a finite range.

Farm Rationale

The reaction of the farmers is difficult to interpret. One normally accepts the view that farmers are economically rational; nevertheless, it appears that in the case of São Paulo they are using uneconomical levels of fertilizer. One explanation is that farmers are still experimenting to determine optimum fertilization levels as the use of fertilizer is a recent phenomenon. They appear to be oriented toward economical use in spite of existing fertilizer recommendations. Remember that the average use of potash is relatively high and this nutrient consistently demonstrated a positive yield response. Nitrogen yielded a negative response and its average use is much below recommended levels. These factors suggest that recommendations may need to be revised in light of research results at the farm level.

Another question is that of the total fertilizer marketing system. Most of fertilizer used in São Paulo is premixed, and although there are many formulas, there are a limited number of nutrient combinations from which farmers can choose. Banks often require that farmers use recommended formulas and application rates as a qualification for obtaining credit. Thus farmers are forced to use fertilizer mixtures which may not be optimum for his specific conditions. With a very favorable credit situation, farmers have been encouraged to use large quantities of fertilizer without sufficient attention to real needs and correct application.

Finally, some interviewed farmers claimed that the quality control in manufacture and distribution of fertilizer was inadequate. Although there were instances of false or inaccurate labeling, it is not believed that this has been responsible for a significant part of lack of response to fertilizer.

Conclusions and Recommendations

The results of this research reveal that, in 1969/70, the value of the marginal product of fertilizer applied on annual crops generally was negative in a region considered to be one of the most progressive and productive in the state of São Paulo. One implication of this finding is that the farmers cannot economically increase their fertilizer application rates even though the actual use of fertilizer per hectare is quite low in comparison to many other countries. If the value of the marginal product of fertilizer continues to be insignificant or negative at present use levels in these crops, it is probable that farmers, based on their own experience, will eventually reduce fertilization rates or, at least, change the nutrient combinations. Increases in national fertilizer consumption will depend principally on adoption by farmers who are not presently using fertilizer or use on crops more sensitive to fertilizer. Nevertheless, the rate of increase in agricultural income and capital depends on higher levels of productivity being obtained by means of greater use of modern inputs, including fertilizer. Fertilizer, as opposed to other types of inputs, has an important advantage as its impact tends to be neutral with respect to farm size.

It is doubtful that the response to fertilization will be greater in other regions as indicated by the review of other studies. If this implication is correct, one may conclude that additional fertilizer use will not contribute substantially to increasing agricultural productivity. It appears that in the case of fertilizers, there are important technological barriers which must be broken before present agricultural policies can stimulate modernization of agriculture through significant increases in productivity.

An implication of these results for agricultural development is that intervention in the market can be an important stimulant for growth in the short run. But it cannot stimulate modernization and productivity in the absence of reliable information on profitable alternatives at the farm level. Brazil stressed relatively easy policy means of increasing productivity, but now confronts a difficult task of providing basic research. Large scale agronomic research efforts are needed to supply the basis for the next step in the agricultural development of the country.

In addition to the research which is primarily agronomic, there are several issues which are in the realm of economics. An evaluation of Brazil's present fertilizer program with regard to its benefits and costs needs to be undertaken. This analysis should consider alternative programs such as focusing the fertilizer program at the extensive margin, i.e., areas in which fertilizer is not presently used, or concentrating on agronomic research. There are also several other questions to be answered. How and where are recommended fertilization rates determined? What are the possibilities to use on-farm experimental plots to generate recommended rates? How important are soil and climate differences within regions with respect to the economics of fertilizer use? Is there a quality control problem within the marketing system? Does there exist a lack of information on optimum methods of applying fertilizer?

Millions of dollars have been spent in granting price and credit concessions for fertilizer use in Brazil without adequate knowledge of their payoffs. It would be economically desirable to transfer a portion of these funds to determine the effect of past expenditures and to investigate ways to increase the profitability of fertilizer utilization in the future.

Footnotes

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1. Estimates of the U.S. Department of Agriculture as quoted by Montague Yudelman, (24, p. 52).

2. Estimates of a FAO/CEPAL/BID study as quoted by Ibid, (24, p. 54).

3. Further description of sampling procedure, characteristics of the farms and region, and can be found in Kelso Wessel and William C. Nelson (23), Leda R. Perroco and others (16), or William C. Nelson (14).

4. Other equations were estimated using different variable combinations in both Cobb-Douglas and quadratic forms.

5. Aggregate yield index based on 1.00 (corn yield) plus 1.07 (cotton yield) plus 2.15 (rice yield) plus 2.87 (soybean yield). Weights are based on the relative values per unit of crops with respect to corn.

6. Biserra (4) used 124 of these same interviews to test the marginal revenue of inputs in corn production in Guaira and Sales de Oliveira. Using a Cobb-Douglas production function and regressing the value of fertilizer against the total value of corn per farm, he concluded that the use of fertilizer was approximately at optimum levels. Nevertheless, he reported the results of other models, based on value per hectare, with small or negative fertilizer coefficients, suggesting the use of fertilizer at other than optimum levels.

7. The observations were divided into groups of high and low levels of fertilizer use. The criteria used for inclusion in the high group varied by crop. For corn, rice and soybeans, observations were included if the application of nitrogen exceeded 21 kg/ha. or phosphate or potash exceeded 41 kg./ha. For cotton, the limits were raised to 83 kg./ha. All observations with fertilizer utilization less than these quantities were included in the low group.

8. The value of the marginal products were based on coefficients from Cobb-Douglas functions similar to Models 1 and 2, Table 2.

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